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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL
LABORATORY, HARVARD UNIVERSITY.

ON ELECTRICAL PROPERTIES OF CRYSTALS.

I. STRATIFICATION AND CAPACITY OF CARBORUNDUM.

BY GEORGE W. PIERCE AND RHYS D. EVANS.

Presented by G. W. Pierce, February 14, 1912. Received February 1, 1912.

THIS work is a continuation of some investigations by one of us on Crystal Rectifiers for Alternating Currents.[1]

Capacity of Carborundum. — In the experiments that are described in the present paper it has been found that a fragment of carborundum, with certain attachments of the electrodes, shows a large electrostatic capacity. Measurements are given of this capacity in two typical cases.

Character of the Phenomenon. — The discussion of the measurements is followed by an account of a microscopic and electrical investigation of the carborundum, which shows that the carborundum crystal is made up of an insulating mass permeated by fine layers of conducting material. These conducting layers are nearly parallel, and, separated as they are in the crystal by non-conducting sheets, form a *natural electrical condenser*, provided electrical contacts are made to two conducting layers or sets of layers that do not happen to short-circuit within the crystal.

METHOD OF MEASURING THE CAPACITY OF THE CRYSTALS.

Method of Charge and Discharge. — The capacity of the carborundum crystals was measured directly by a method of charge and discharge. A simplified diagram of the circuits employed is shown in Figure 1. By means of a motor-driven commutator C the crystal Cr was connected alternately first with the charge circuit VG′Cr and then with the discharge circuit CrG. A galvanometer, used for measuring the current out of or into the crystal, could be placed either in the discharge circuit at G or in the charge circuit at G′.

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[1] G. W. Pierce: "Crystal Rectifiers for Electric Currents," Part I, Physical Review, **25**, pp. 31–60, 1907; Part II, ibid., **28**, pp. 153–187, 1909, and These Proceedings, **44**, pp. 317–349, 1909; Part III, Physical Review, **29**, pp. 478–484, 1909. See also "A Simple Method of Measuring the Intensity of Sound," These Proceedings, **43**, 1908, and "Principles of Wireless Telegraphy," McGraw-Hill, New York, 1910.

When the galvanometer was placed at G and allowed to come to a steady reading, while the commutator C was in operation, the reading of the galvanometer gave the discharge current made up of a series of discharge impulses from the crystal. Placed at G′, the steady deflection of the galvanometer, with the commutator in operation, gave the charge current made up of charge impulses going into the crystal.

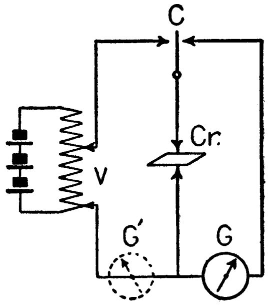

Figure 1. Circuit employed in capacity measurements.

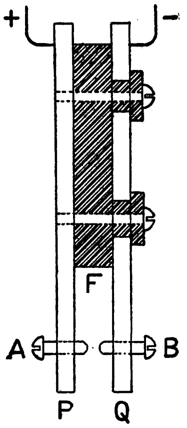

Figure 2. Clamp for holding specimen between screws A and B.

The Commutator. — The commutator was made of cold-rolled copper and was used with brushes of the same material so as to avoid thermoelectric currents in this part of the apparatus.

In order to minimize the leak current, the segments of the commutator and the brushes pressing against them were so arranged as to make the time of open circuit between charge and discharge as small as possible.

In order to simplify the interpretation of results, the time of contact for charge was made approximately equal to the time of contact for discharge.

Measurement of Frequency of Commutation. — Various speeds of the commutator were obtained by the use of a series of pulleys of different sizes on the axle of the motor and a corresponding series of different-sized pulleys on the axle of the commutator, which was driven by a belt from the motor. The speed of the commutator was measured by putting a standard mica condenser in the place of the crystal Cr of Figure 1, and reading the galvanometer at G with a known impressed voltage. In practice, in order to eliminate any errors arising from lack of proportionality of the galvanometer deflections, the impressed voltage was varied so that the readings of the galvanometer in the speed determinations were brought always to the same deflection (20 cm.), under which condition the number of charges or discharges per second was inversely proportional to the voltage required to give the standard deflection.

While the galvanometer deflection and voltage were under observation, one of these speeds was found absolutely by means of a revolution-counter attached to the shaft of the commutator, and the other speeds were then known in terms of the speed given by the revolution counter.

The capacity method of measuring the frequency of charges or discharges had the advantage of permitting instantaneous observations of the constancy of the commutator speed before and after measurements with the crystal as condenser.

Measurements Capable of Repetition. — Although the adjustment of the electrodes upon the crystal so as to get the capacity effects afforded some difficulty, yet when the adjustments were once made, the galvanometer readings, under given conditions, were about as constant with the crystal as capacity as with the standard mica condenser as capacity, and all the observations, with ordinary precautions, were capable of repetition with an error of about 1 per cent, which represented the irregularities of the speed of the commutator.

Galvanometer. — A D'Arsonval Galvanometer of 2000 ohms resistance was used. This galvanometer was provided with a heavy closed-coil electromagnetic damper, so as to obtain steady deflections even with comparatively slow speeds of the commutator. High resistance or high inductance in the galvanometer used with this method of determining capacity, if the capacity is large, is objectionable, because of the danger of having incomplete charge or discharge. In the present experiments attention was given to the matter of the completeness or incompleteness of the charge or discharge. In one of the experiments described below (Experiment II.) the charges and discharges were probably incomplete, but this was due not to the resistance or inductance of the galvanometer, but to the high resistance of the conducting sheets which served, in the crystal, as armatures of the condenser or else to the high resistance of the contacts of the electrodes with these sheets.

EXPERIMENT I.

Crystal held in a Clamp. — In this experiment a flat piece of carborundum, about 1 mm. thick, was clamped between two screws A and B of Figure 2. These screws passed through brass supports P and Q insulated from each other by a fibre block F. The screws had copper-plated ends, and were screwed down upon the specimen with sufficient pressure to cause the brass supporting strips (1 cm. wide and 1.5 mm. thick) to spring apart perceptibly. Later experiments showed that the amount of this pressure probably has no influence on the capacity, so long as the increase or decrease of pressure does not change the position of the contacts with respect to the conducting laminae.

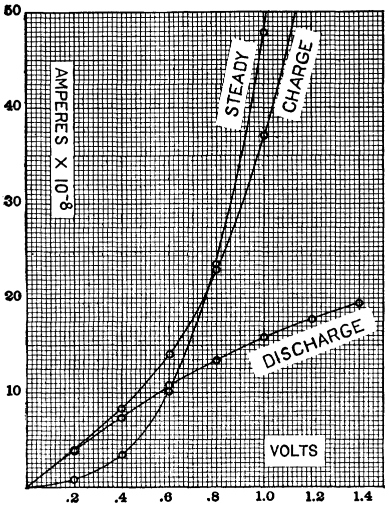

FIGURE 3. Current *vs.* voltage. A positive. $n = 24.2$.

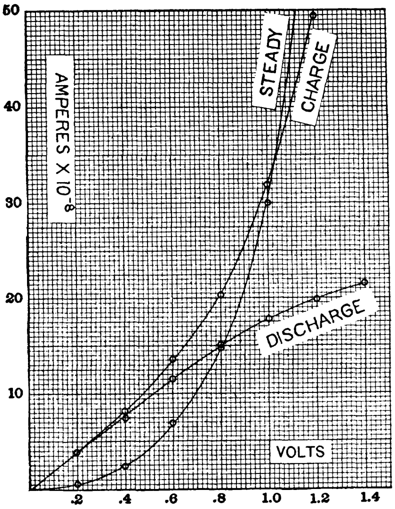

FIGURE 4. Current *vs.* voltage. B positive. $n = 24.2$.

Choice of Specimen. — The particular specimen used in this experiment and the particular setting of the crystal between the supports was obtained only by groping. It had been found accidentally that a specimen of carborundum used in temperature measurements of conductivity showed a slight capacity effect. Incited by this observation, we selected a large number of pieces of carborundum and put them one after the other in the clamp and tested for capacity. Most of them showed no capacity. Finally the piece used in this experiment was tried with the adjustment that happened to give the capacity effect in a marked degree.[2] Then without changing the adjustment a complete set of data with different speeds and different applied voltages was taken. After the experiment was completed, the specimen was examined with a microscope and was explored electrically while under the microscope, and the existence of the conducting laminae separated by insulating sheets was discovered. After the discovery of these laminae, other specimens could be selected and, with a somewhat difficult adjustment of the electrodes against the conducting laminae, could be shown to act as condensers with larger capacity in some cases than that of the specimens with which the present data were obtained.

Data with Specimen I. — Table I. following contains values of the charge and discharge current obtained with Specimen I, in a circuit of the form of Figure 1, under various impressed voltages and for various numbers of charges and discharges per second. The crystal was connected into the circuit so that one side should be positively charged (see column headed "A positive") and then, without changing the adjustment of the specimen in the clamp, the leads to the crystal were reversed so that it should be charged with the other side positive (see column headed "B positive").

Charge and Discharge Current not a Linear Function of the Voltage. — From these data, sample curves of charge and discharge current plotted as a function of the impressed voltage, with $n = 24.2$, are given, in Figure 3, with the charge applied so that the side A was positive, and in Figure 4 with the charge applied in the opposite direction. Along with the "charge" and "discharge" curves there is plotted, in each figure, a curve of steady current through the crystal obtained when the various voltages were applied directly in circuit with the crystal and galvanometer without the intermediation of the commutator. These curves, which are marked "steady," are the *current-voltage characteristics* of the crystal in the two opposite directions.

The curves of Figures 3 and 4 show that the charge and discharge

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[2] In his testimony, on May 22, 1911, in the case of the National Electric Signaling Company *vs.* The United Wireless Telegraph Company, Equity No. 643, District of Maine, Dr. Louis Cohen stated that a certain carborundum detector had a capacity of about .004 microfarads. This result he obtained by measurements with a high frequency generator of 72,500 cycles. So far as we know, his result has not been published except in the Court Record. Dr. Cohen gave no explanation of the phenomenon.

Our own discovery of the capacity was made before the date of Dr. Cohen's experiments, and our delay in publication has been occasioned by a long and tedious search for the explanation of the phenomenon, which we believe we have now found.

TABLE I.

OBSERVATIONS IN MEASUREMENT OF THE CAPACITY OF SPECIMEN I.

No. of Charges or Discharges per Second, n.	Impressed Voltage E in Volts.	Current in Amperes × 10^{-8}.			
		A Positive.		B Positive.	
		Charge.	Discharge.	Charge.	Discharge.
11.43 for A positive and 11.85 for B positive	.2	2.46	2.14	2.35	2.11
	.4	5.49	4.01	5.20	4.22
	.6	10.00	5.80	8.87	6.36
	.8	17.90	7.17	15,00	7.85
	1.0		8.23		8.75
	1.2		9.26		9.50
	1.4		10.22		10.27
16.60 for A positive and 16.90 for B positive	.2	3.17	2.80	3.30	2.71
	.4	6.80	5.54	6.85	5.60
	.6	11.70	8.05	11.33	8.72
	.8	20.00	10.02	18.04	11.04
	1.0		11.65		12.79
	1.2		13.20		14.20
	1.4		14.25		15.55
20.0 for A positive and 20.4 for B positive	.2	3.43	3.20	3.43	3.16
	.4	7.25	6.34	7.40	6.62
	.6	12.40	9.00	12.13	10.00
	.8	20.4	11.17	19.30	12.75
	1.0		12.70		14.80
	1.2		13.98		16.35
	1.4		14.80		17.84
24.3 for A positive and 24.2 for B positive	.2	3.94	3.62	3.94	3.64
	.4	8.36	7.34	8.21	7.47
	.6	14.00	10.73	13.35	11.50
	.8	23.05	13.50	20.30	15.04
	1.0		15.83		17.75
	1.2		17.70		19.80
	1.4		19.50		21.60
29.1 for A positive and 29.5 for B positive	.2	4.41	4.17	4.43	4.25
	.4	9.21	8.23	9.22	8.71
	.6	15.10	12.10	14.80	13.30
	.8	23.75	15.32	22.40	17.40
	1.0		17.83		20.32
	1.2		20.05		22.90
	1.4		21.90		24.40
32.7 for A positive and 33.1 for B positive	.2	5.02	4.43	5.01	4.75
	.4	10.30	9.25	10.56	9.75
	.6	16.85	13.70	16.77	15.25
	.8	25.90	17.30	25.02	20.20
	1.0		20.60		23.80
	1.2		23.20		26.85
	1.4		25.65		29.60
39.80 for A positive and 39.83 for B positive	.2	5.67	5.36	5.78	5.28
	.4	11.80	10.77	11.96	11.12
	.6	19.10	15.91	19.33	17.16
	.8	30.35	20.54	28.40	23.03
	1.0		24.75		27.95
	1.2		28.20		31.95
	1.4		31.45		35.10

current obtained with this specimen is not a linear function of the applied e. m. f. This might have been anticipated from the fact that the leak current through the crystal which increases the charge current and diminishes the discharge current is not a linear function of the voltage.

TABLE II.

EQUATIONS OF CURRENT AS FUNCTION OF n.

Impressed Voltage E.	Charge Equation.	Discharge Equation.
WITH A POSITIVE.		
.2	$I_1 \times 10^8 = 1.3 + 1.12\,n$	$I_2 \times 10^8 = .9 + 1.10\,n$
.4	$3.0 + 2.25\,n$	$1.8 + 2.24\,n$
.6	$6.3 + 3.33\,n$	$1.8 + 3.46\,n$
.8	$13.3 + 4.02\,n$	$1.5 + 4.80\,n$
1.0		$1.5 + 5.85\,n$
1.2		$1.6 + 6.72\,n$
1.4		$1.9 + 7.28\,n$
WITH B POSITIVE.		
.2	$I_1 \times 10^8 = 1.0 + 1.20\,n$	$I_2 \times 10^8 = .7 + 1.20\,n$
.4	$2.3 + 2.45\,n$	$1.4 + 2.46\,n$
.6	$4.4 + 3.74\,n$	$2.3 + 3.74\,n$
.8	$9.3 + 4.82\,n$	$1.7 + 5.44\,n$
1.0		$1.4 + 6.66\,n$
1.2		$.6 + 7.87\,n$
1.4		$-.1 + 8.35\,n$

Charge and Discharge Currents are Linear Functions of n. — If, instead of being plotted against voltage, the charge and discharge current-readings be plotted against the number of charges and discharges per second, the curves of Figures 5, 6, 7, and 8 are obtained. These curves show that with either orientation of the crystal ("A positive" or "B positive") the current-reading of the galvanometer on charge or on discharge is a linear function of the number of charges or discharges per second.

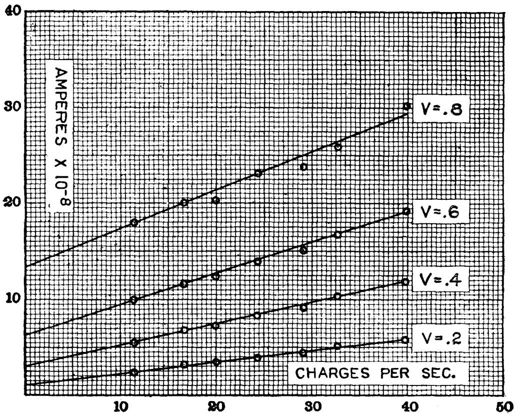

FIGURE 5. A positive. Charge current *vs.* no. charges per second, for various applied voltages *v*.

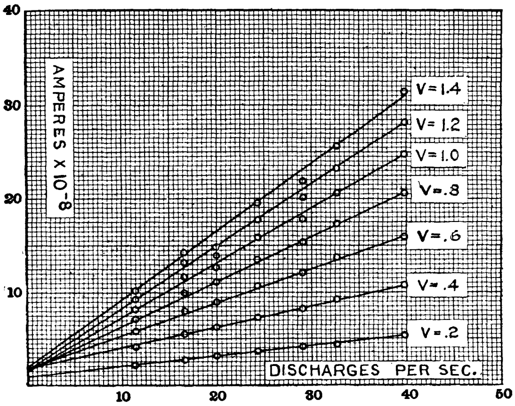

FIGURE 6. A positive. Discharge current *vs.* no. discharges per second, for various applied voltages *v*.

The empirical equations of the curves of Figures 5 to 8, as taken from the curves, are given in Table II. above.

The equations of Table II. agree closely with the data of Table I. The simplicity of these equations indicates that we are dealing with an orderly phenomenon. The linear relation between charge or discharge current and number of charges or discharges per second, we have taken to indicate that the charge and discharge were practically complete at each commutation; for it is apparent that if this charge or discharge were not complete the incompleteness would be greater at the higher frequencies of commutation and we should not have the linear relation.

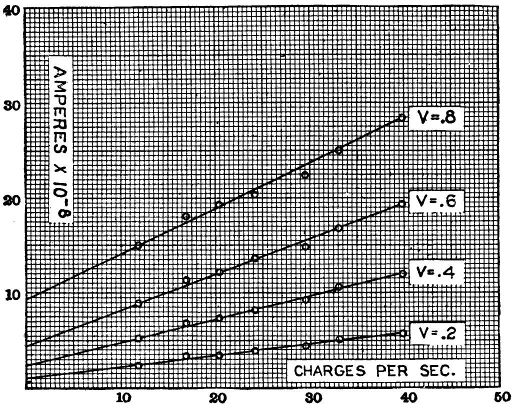

FIGURE 7. B positive. Charge current *vs.* no. charges per second.

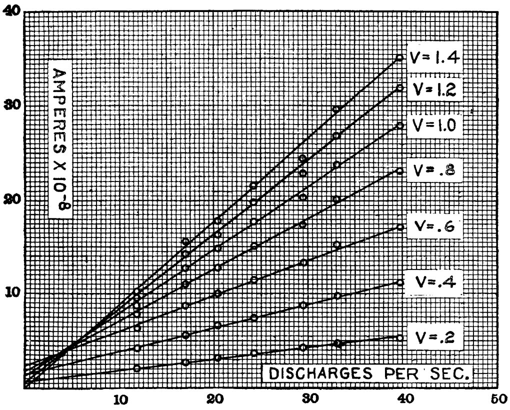

FIGURE 8. B positive. Discharge current *vs.* no. discharges per second.

There follows a mathematical investigation of the phenomenon with the assumption of a complete charge and discharge at each cycle of the commutator. The problem is an interesting one on account of the fact that the leak current through the crystal is not proportional to the voltage.

Theory of Action of Crystal as a Leaky Condenser on the Assumption that Charge and Discharge are Complete.

Let us suppose an e. m. f. E (Figure 9) to be applied to a condenser C through a resistance R, and suppose that the condenser is shunted by a resistance r, through which the leak occurs — the resistance r being of such a character that the current through it is not proportional to the voltage.

Let $x =$ the feed current in the main lead R,

$y =$ the leak current through r,

$v =$ difference of potential between the ends of the resistance r; this is a function of y, and is also the p. d. between the plates of the condenser.

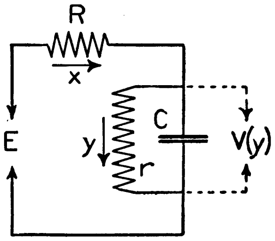

FIGURE 9.

These quantities, x, y, and v are functions of the time t.

Kirchhoff's laws give the following equations:

$$E = Rx + v, \tag{1}$$

obtained by taking the e. m. f. around the circuit $ERCr.$; and

$$\int (x - y)dt = Cv, \tag{2}$$

since $(x - y)$ is the current charging the crystal capacity.

By integration of equation (2) from $t = 0$ to $t = T$, we have

$$q_1 = \int_0^T xdt = C(v_T - v_0) + \int_0^T ydt, \tag{3}$$

in which q_1 is the quantity of electricity flowing through the charge leads during the time T of one complete connection of the condenser to the charging e. m. f.

If we suppose the previous discharge of the condenser to have been complete

$$v_0 = 0. \tag{4}$$

If also we suppose the charge of the condenser is complete in the time T, the current x flowing through the leads at time T is Y, where Y is the steady current through the crystal under the impressed e. m. f. E; therefore, by equation (1), we have

$$v_T = E - RY. \tag{5}$$

Whence equation (3) becomes

$$q_1 = (E - RY)C + \int_0^T y dt. \tag{6}$$

With n charges of the condenser per second, we have for the galvanometer current-reading I_1 in the charge circuit $I_1 = nq_1$; whence

$$I_1 = nC(E - RY) + n \int_0^T y dt. \tag{7}$$

In this equation R is the resistance of the charge circuit from the source of e. m. f. up to the point at which the charge is deposited on the condenser. This includes the resistance of the galvanometer, the resistance of the contacts of the electrodes with the conducting laminae, and the resistance of these laminae up to the point of leak.

Equation (7) is an exact expression for the current-reading of the galvanometer in the charge circuit when the commutator is driven so as not to exceed the speed at which the charge of the condenser at each impulse is complete.

Equation (7), therefore, holds for

$$T \geqq \tau$$

in which T is the time during which the condenser is in charge relation to the circuit during one cycle of the commutator, and τ is the interval required for practically complete charging of the condenser. Let us now break up the last term of equation (7) into two integrals, one from zero to τ and the other from τ to T. During the first of these intervals the leak current $y = y_1$ (say) is variable, and during the second interval the leak current $y = Y$ (say) is constant. Then we have

$$I_1 = nC(E - RY) + n \int_0^\tau y_1 dt + n \int_\tau^T Y dt,$$

in which y_1 is the variable leak current during the short interval for the potential of the condenser to attain substantially its final value, and Y is the steady current through the crystal and the leads under the steady e. m. f. E during the remainder of its connection with the charge circuit. The steady-leak term may be integrated, and we have after integration

$$I_1 = nC(E - RY) + nY(T - \tau) + n\int_0^{\tau} y_1 dt. \qquad (8)$$

Now it should be noted that the quantity nT is independent of the speed, since the geometrical dimensions of the commutator, which is of the rotating type, are fixed. The value of nT is $1/p$, — this quantity $1/p$ being the part of the whole circumference of the commutator occupied by the charge segment. Replacing nT by its value $1/p$, we have

$$I_1 = \frac{Y}{p} + n\{CE - RYC - Y\tau + \int_0^{\tau} y_1 dt\}. \qquad (9)$$

In equation (9) τ is arbitrarily defined as the time for a practically complete charge. Let us be a little more specific and suppose that τ is of such value that when substituted for t in the exponential expression $e^{-\frac{t}{RC}}$ it reduces this exponential to .006. This would make the charge complete so far as measurements of the accuracy of the present experiment would show. If

$$e^{-\frac{\tau}{RC}} = .006,$$

$$\tau = 5RC \text{ (by tables of exponentials).} \qquad (10)$$

With this definition of τ equation (9) becomes

$$I_1 = \frac{Y}{p} + n\{CE - 6RYC + \int_0^{5RC} y_1 dt\}. \qquad (11)$$

This is the equation of current-reading of the galvanometer in the leads to the crystal during *charge.*

Let us next examine briefly the theoretical problem of the *discharge* of the crystal condenser.

A mathematical treatment similar to that of the charge shows that the current-reading of the galvanometer in the discharge circuit, if there are n discharges per second, is

$$I_2 = nCE_0 - n\int_0^{5RC} y_2 dt, \qquad (12)$$

in which y_2 is the leak current during discharge and E_0 is the potential of the condenser at the beginning of the discharge. The potential of the condenser at the beginning of the discharge is less than E the applied e. m. f. for two reasons; first, because on account of the leak, the crystal was not charged to the applied e. m. f.; and second, because there has been a small loss of charge during the insulation time while the commutator was changing from charge to discharge.

As may be seen by reference to equation (5) the deficiency of potential due to the first of these causes is RY. The fall of potential due to the second of these causes is $\frac{1}{C}\int_0^{T_2} y_3 dt$, in which y_3 is the leak current during insulation, and T_2 is the length of time of the insulation period during each cycle. Therefore the current reading of the galvanometer in the discharge circuit is

$$I_2 = n\,\{CE - RYC - \int_0^{T_2} y_3 dt - \int_0^{5RC} y_2 dt\}. \qquad (13)$$

This is the exact equation on *discharge.*

As an approximation let us suppose that the leak current during insulation was constant and equal to its value at the end of the preceding charge. This is approximately true, because the insulation time was short. With the approximation we have

$$n\int_0^{T_2} y_3 dt = nYT_2 \qquad (14)$$

$$= \frac{Y}{m},$$ in which $\frac{1}{m}$ is the part of the commutator circumference occupied by the insulation segment. With this approximation equation (13) becomes

$$I_2 = -\frac{Y}{m} + n\{CE - RYC - \int_0^{5RC} y_2 dt\}, \quad \text{(approx.)} \qquad (15)$$

in which the first term Y/m is a little too large.

Examination of the Data of Experiment I.

In order to compare the data of Experiment I. with the theoretical equations for charge and discharge current derived above, let us write the charge equation (11) in the form

$$I_1 = \frac{Y}{p} + nEC'_1, \qquad (16)$$

in which C'_1 is related to the capacity C by the equation

$$C = \frac{C'_1}{1 - \frac{6RY}{E} + \frac{1}{CE}\int_0^{5RC} y_1 dt}. \tag{17}$$

Likewise writing the discharge equation (15) in the form

$$I_2 = -\frac{Y}{m} + nEC'_2, \tag{18}$$

in which C'_2 is related to the capacity C by the equation

$$C = \frac{C'_2}{1 - \frac{RY}{E} - \frac{1}{CE}\int_0^{5RC} y_2 dt}. \tag{19}$$

Let us now tabulate the values of C'_1 and C'_2 obtained from the experimental data. These quantities which we shall call approximate values of capacity are obtained by dividing the coefficients of n of the equations of Table II. by the corresponding values of E, and are collected in Table III.

In the attempt to get a nearer approximation to the capacity in terms of these coefficients C'_1 and C'_2, it should be noted that the integral terms of equations (17) and (19) are greater than would be obtained by putting y_1 and y_2 respectively equal to zero, and are less than would be obtained by setting y_1 and y_2 equal to their greatest value Y; whence it may be seen from equation (17) and equation (19) respectively that

$$\frac{C'_1}{1 - \frac{6RY}{E}} > C > \frac{C'_1}{1 - \frac{RY}{E}}, \tag{20}$$

and

$$\frac{C'_2}{1 - \frac{6RY}{E}} > C > \frac{C'_2}{1 - \frac{RY}{E}}, \tag{21}$$

in which C is the capacity.

It is, therefore, evident that C, the capacity of the crystal, is greater than the coefficients C'_1 or C'_2 of Table III.

In the attempt to ascertain whether or not the resistance terms could influence the coefficients sufficiently to account for the large excess of these coefficients with B positive over the corresponding values of A positive, or whether on the other hand it is necessary to assume different capacities in the two opposite directions, we have computed approximate values of the integrals in the denominators of equations (17) and (19). These computations were made by omitting second-order effects and assuming that the electromotive force on charge is $v_1 = E(1 - e^{-\frac{t}{RC}})$, and on discharge $v_2 = Ee^{-\frac{t}{RC}}$. With these values of the e. m. f. as functions of t/RC and with the steady current-voltage curves of Figures 3 and 4, y_1 and y_2 were plotted as functions of t/RC and integrated by measuring areas, with the result, which is only an approximation, that on charge [3]

TABLE III.

Applied Voltage E, Volts.	Approximate Value of Capacity of Specimen I.			
	With A Positive.		With B Positive.	
	C'_1 Farads Charge.	C'_2 Farads Discharge.	C'_1 Farads Charge.	C'_2 Farads Discharge.
.2	$.560 \times 10^{-8}$	$.550 \times 10^{-8}$	$.600 \times 10^{-8}$	$.600 \times 10^{-8}$
.4	.562	.560	.612	.615
.6	.555	.580	.623	.623
.8	.503	.600	.603	.681
1.0		.585		.666
1.2		.560		.656
1.4		.520		.632
average	.545	.565	.619	.639

$$C'_1 = C\left(1 - \frac{2.6R}{\rho}\right), \tag{22}$$

---

[3] An independent investigation of the problem imposing the condition that the leak resistance obey *Ohm's law* (i. e. is independent of voltage) leads also exactly to equation (16) for charge and to equation (18) for discharge, with, however, $C'_1 = C'_2 = \frac{C}{\left(1 + \frac{R}{\rho}\right)^2} = C\left(1 - \frac{2R}{\rho}\right)$, approximately.

and on discharge

$$C'_2 = C\left(1 - 1.5\frac{R}{\rho}\right), \qquad (23)$$

in which R is the resistance from the impressed e. m. f. into the condenser, and ρ is equal to Y/E and is the resistance to steady e. m. f. of the circuit from the source of e. m. f. through the leads and through the plates and dielectric of the condenser. The resistance ρ is a function of E and is smaller the greater E is.

These equations are consistent with the fact that the coefficient C'_2 on discharge is greater than the coefficient C'_1 on charge. This is seen from Table III. to be true both for A positive and for B positive. Now the current-voltage curves of Figures 3 and 4 show that ρ is smaller for A positive than for B positive. This would make the coefficients for B positive smaller than those for A positive, whereas the converse is the case. In order to explain this discrepancy it is necessary to suppose either

(1) that the capacity of the crystal condenser is actually greater in direction B positive than in the opposite direction, or

(2) that the resistance R is also a function of E and decreases with increasing E more rapidly than ρ does.

The second of these propositions is entirely consistent with previous experiments with carborundum crystals, which showed that if the electrodes were plated to the specimen a large part of the dependence of resistance on current disappeared.

We cannot, however, be sure that the apparent inequality of capacity in the two opposite directions is entirely an effect of leak current; for we give next data obtained with another specimen with which the leakage through the crystal is almost entirely absent, and yet the capacity given by the measurements is different in the two opposite directions.

Experiment II. Specimen with very Small Leakage.

Mounting in Wood's Metal. — This specimen of carborundum was mounted in a metallic cup in a matrix of Wood's metal. The Wood's metal which served as a solder was placed in the cup and was melted. The specimen was pushed into the molten solder and held with all but its upper face submerged until the solder solidified, forming a close-fitting mold about the specimen. The cup served as one electrode. The other electrode was a pointed brass rod brought down upon the crystal and held by a spring. The cup containing the specimen was

TABLE IV.

DATA IN MEASUREMENT OF THE CAPACITY OF SPECIMEN II.

No. of Charges or Discharges per Second, n.	Impressed e. m. f. E. in Volts.	Current in Amperes $\times 10^{-7}$.			
		Point Positive.		Point Negative.	
		Charge.	Discharge.	Charge.	Discharge.
11.0	.3			.787	.787
	.6	1.43	1.43	1.66	1.64
	.9	2.07	2.06	2.71	2.54
	1.2	2.68	2.66	4.48	3.52
16.7	.3			1.16	1.16
	.6	2.14	2.14	2.46	2.43
	.9	3.18	3.17	3.98	3.81
	1.2	4.05	4.03	6.20	5.34
22.5	.3			1.59	1.59
	.6	2.92	2.92	3.30	3.27
	.9	4.30	4.29	5.41	5.22
	1.2	5.61	5.59	8.04	7.26
30.9	.3			2.16	2.16
	.6	3.97	3.97	4.42	4.39
	.9	5.92	5.89	7.17	7.02
	1.2	7.64	7.60	10.7	10.0
38.3	.3			2.60	2.60
	.6	4.81	4.78	5.40	5.37
	.9	7.15	7.15	8.72	8.54
	1.2	9.18	9.10	12.75	12.08
46.2	.3				
	.6	5.67	5.67	6.37	6.33
	.9	8.30	8.34	10.17	10.00
	1.2	10.67	10.67	14.76	14.10
54.6	.3			3.48	3.38
	.6	6.41	6.40	7.35	7.34
	.9	9.50	9.50	11.41	11.27
	1.2	12.50	12.30	16.45	15.85

carried by a mechanical microscope stage, so that the specimen could be moved around under the point terminal until a point of contact that gave the capacity effect was located by the capacity measurements. The pressure of the point electrode was then increased so as to avoid accidental disturbance of the connections during the measurements of capacity.

Data. — Current-readings on charge and discharge were taken with the crystal charged so that the point electrode was positive and then with the point electrode negative. Table IV. contains the record.

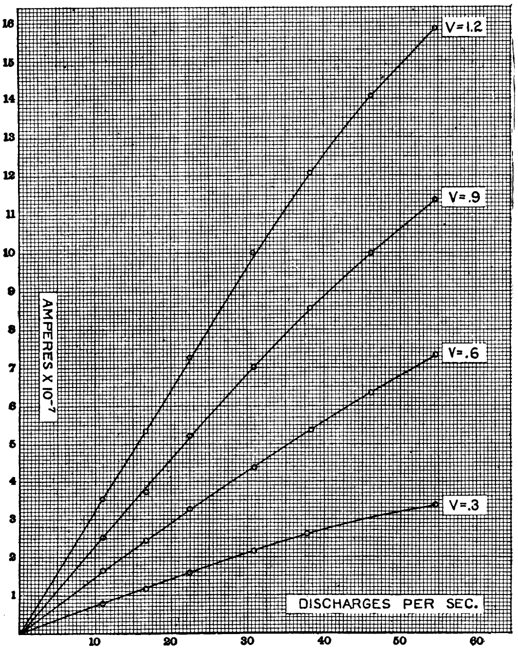

FIGURE 10. Point negative. Discharge current *vs. n*, for various applied voltages *v*.

By a reference to Table IV. it will be seen that with the crystal charged so that the point was positive this specimen gives the same current on discharge as on charge. With this direction of charging *the crystal condenser shows practically no leak.* Table V., which contains the steady current-voltage data for this specimen, shows also that with this direction of application of the e. m. f. the crystal lets through only $.09 \times 10^{-7}$ amperes at 1.2 volts. With the e. m. f. applied in the opposite direction (point negative) the charge and discharge currents (Table IV.) differ by about 5 per cent, at the highest voltage, 1.2 volts. At .9 volts, and lower, this difference is one per cent or less. With the point negative the steady current at 1.2 volts amounts to 1.79 × 10^{-7} amperes as is seen in Table V. Therefore the crystal with the point charged negative is not non-leaky as with the opposite direction of charging, but the leak is so small as to make the analysis of the problem much more satisfactory than with Specimen I.

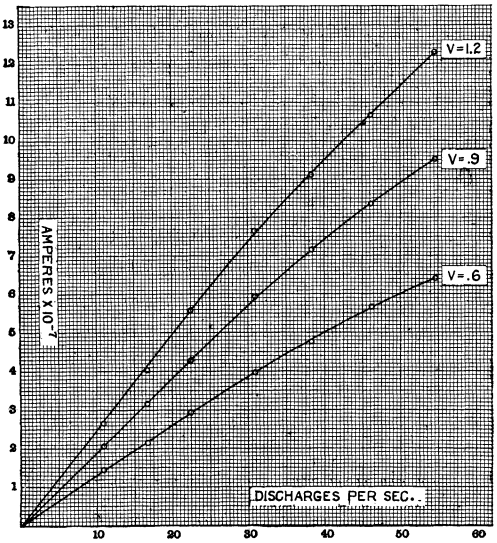

Figure 11. Point positive. Discharge current *vs.* n, for various applied voltages v.

Figures 11 and 10 show the discharge current plotted against n, the number of discharges per second, obtained with point positive and point negative respectively. The corresponding charge curves depart so slightly from the discharge curves that they are not here reproduced.

All of the charge and discharge curves for this specimen pass through the origin. This is a result such as one obtains with an ordinary condenser possessing no leakage.

The curves all droop at higher values of n, but are nearly straight for small values of n. Now this fact is in agreement with results obtained with good condensers provided they possess such high resistance in the charge or discharge circuit that the charge and discharge are incomplete. It is interesting that the treatment of the experimental curves of Figures 10 and 11 as due to a condenser with incomplete charge and discharge leads to the result that the capacity is independent of *n* but is dependent, as in Experiment I., upon the magnitude and *direction* of the impressed e. m. f. We shall give a brief derivation of the formula for multiple incomplete charge and discharge.

SKETCH OF THEORY OF MULTIPLE INCOMPLETE CONDENSER DISCHARGE.

Let a condenser of capacity C be alternately charged and discharged through a resistance R which is so great as to permit only a partial charge or discharge in the time T of one connection of the condenser into the charge or discharge circuit.

Let the applied e. m. f. on charge be E, and suppose that the charge and discharge have been repeated until a final state is reached.

Let q_1 = quantity of electricity in the condenser at the end of a charge,
q_0 = the quantity in the condenser at the end of a discharge.

If we write down the differential equation for the quantity in the condenser on charge and integrate it subject to the conditions of the problem, we obtain

$$q_1 = q_0 e^{-\frac{T}{RC}} + CE\left(1 - e^{-\frac{T}{RC}}\right). \tag{24}$$

Similarly from the differential equation for discharge we get

$$q_0 = q_1 e^{-\frac{T}{RC}}. \tag{25}$$

Eliminating between equations (24) and (25) we have

$$q_1 = \frac{CE}{1 + e^{-\frac{T}{RC}}}.$$

$$q_0 = \frac{CEe^{-\frac{T}{RC}}}{1 + e^{-\frac{T}{RC}}}.$$

The quantity of electricity flowing into the condenser during one charge, or out of the condenser during one discharge, is

$$q = q_1 - q_0 = CE\frac{1 - e^{-\frac{T}{RC}}}{1 + e^{-\frac{T}{RC}}}. \tag{26}$$

This equation by expansion becomes

$$q = CE\left(1 - 2e^{-\frac{T}{RC}} + 2\left(e^{-\frac{T}{RC}}\right)^2 - 2\left(e^{-\frac{T}{RC}}\right)^3 + \ldots.\right). \quad (27)$$

If we may neglect $2\left(e^{-\frac{T}{RC}}\right)^2$ in comparison with unity, equation (27) becomes

$$q = CE\left(1 - 2e^{-\frac{T}{RC}}\right) \quad \text{approximation.} \quad (28)$$

If there are n charges per second, the current-reading of a galvanometer in the charge or discharge circuit is

$$I = nq,$$

and the time of charge or discharge is

$$T = \frac{1}{pn},$$

where $1/p$ is the fraction of the circumference of the commutator occupied by the charge segment or discharge segment, the two being equal.

With these substitutions equation (28) becomes

$$I = nCE\left(1 - 2e^{-\frac{1}{pnRC}}\right). \quad (29)$$

With the commutator used in these experiments $1/p$ was .48, whence

$$I = nCE\left(1 - 2e^{-\frac{0.48}{nRC}}\right). \quad (30)$$

Examination of the Data of Experiment II.

The curves of discharge current of Figures 10 and 11 with current plotted against number of discharges per second are accurately described by equation (30), as may be seen by reference to Tables VI. and VII., which contain a comparison of observed and calculated values.

The equations of Table VIII. were obtained as follows: Consistent with the theoretical equation (30), the slope of each of the curves of Figures 10 and 11 was taken at the origin. This slope is the coefficient of n in equation (30), and the corresponding coefficient in Table

VIII. Having obtained the slope term, the exponential was next obtained by assuming the upper end point of one of the experimental curves to satisfy equation (30). This gave the exponent $-165/n$, and by trial the same exponent was found to apply approximately to all of the other curves. That is, all the equations of Table VIII. were obtained by employing the slope at the origin of each of the experimental curves, and in addition assuming the exponential equation to be correct for one other point of one of the curves. All of the points of all the curves were then found to be closely given by the equations so derived.

TABLE V.

Steady Current-Voltage Characteristic of Specimen II.

E. m. f. Volts.	Current in 10^{-7} Amperes.	
	Point Positive.	Point Negative.
.3	.004	.012
.6	.02	.083
.9	.04	.45
1.2	.09	1.79
1.5	.165	6.13

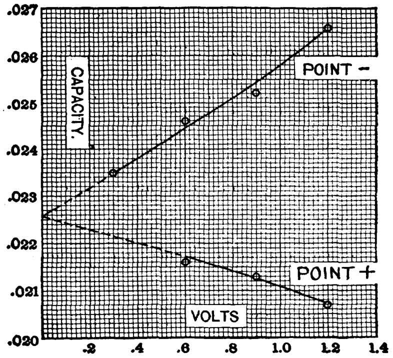

Figure 12. Capacity in microfarads of Specimen II. for different values of applied e. m. f.

The conclusion is that the droop of the several curves of Figures 10 and 11 may be reasonably explained as due to incompleteness of charge and discharge. On this assumption it will be seen that the capacity of the crystal, obtained by dividing the coefficients of the equations of Table VIII. by the corresponding values of *E*, are functions of the applied e. m. f. and of the direction of charge, while the product of *R* by *C*, as given by the exponent, is constant. These quantities are collected in Table IX., and plotted in the curves of Figure 12.

TABLE VI.

Data of Experiment II. Compared with Equation (30).

No. of Discharges per Second, n.	Point Positive. Discharge Current in 10^{-7} Amperes.					
	E = .6.		E = .9.		E = 1.2.	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
11.0	1.43	1.43	2.06	2.11	2.66	2.73
16.7	2.14	2.15	3.17	3.17	4.03	4.09
22.5	2.94	2.94	4.29	4.32	5.59	5.58
30.9	3.97	3.99	5.89	5.90	7.60	7.62
38.3	4.78	4.85	7.15	7.18	9.10	9.26
46.2	6.40	6.42	9.50	9.50	12.30	12.30

The curves of Figure 12 show that the capacity, as given by equation (30), is changed by a mere reversal of the direction of charge. The capacity is the greater when the point electrode is negative, and with this orientation the capacity increases with increase of applied e. m. f. With the opposite direction of application of e. m. f. the capacity is less and decreases with increasing applied e. m. f.

Whether this result is evidence of a unilateral dielectric constant of the carborundum — which seems improbable — or whether the result is due to an imperfect comprehension of the various factors that may enter into the phenomenon and appear in the final coefficient as capacity, we are at present unable to say.

Among the various factors neglected in the mathematical discussion of the data there is the possibility that heat effects may be important. It looks at first glance as if a thermoelectromotive force at the junction of the electrode with one of the laminae of the crystal might aid the charge in one direction of charge and hinder it with the opposite direction of charge, and might, hence, cause differences in the capacity coefficients in the two directions, and might also account for the form of the curves of Figure 12. We have submitted the thermoelectric hypothesis to a mathematical treatment, assuming that both Joulean heat and Peltier heat act at the junction of one of the electrodes with the crystal, and have arrived at the result

TABLE VII.

DATA OF EXPERIMENT II. COMPARED WITH EQUATION (30).

No. of Disch. per Sec., n.	Point Negative. Discharge Current in 10^{-7} Amperes.							
	E = .3.		E = .6.		E = .9.		E = 1.2.	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
11.0	.78	.77	1.64	1.59	2.54	2.52	3.52	3.52
16.7	1.16	1.17	2.43	2.42	3.81	3.80	5.34	5.35
22.5	1.59	1.58	3.27	3.26	5.22	5.11	7.26	7.20
30.9	2.16	2.22	4.39	4.58	7.02	7.17	10.00	10.10
38.3	2.60	2.61	5.37	5.38	8.54	8.45	12.08	11.92
46.2			6.33	6.32	10.00	9.95	14.10	14.30
54.6	3.38	3.48	7.34	7.18	11.27	11.25	15.85	15.85

(1) That the assumption of Joulean heat alone in combination with capacity gives a capacity coefficient that is *the same in the two opposite directions, and for both directions the effect of the heat term is to make the capacity coefficient diminish with increasing applied e. m. f.*

(2) Peltier heat and Joulean heat, if both present in combination with the capacity, would give different capacity coefficients in the two opposite directions, but the effect of the heat would still manifest itself as *an apparent decrease of capacity with increase of applied e. m. f. for both directions of application of the e. m. f.*

Neither of these results is in complete accord with the experimental facts.

Various other possible explanations of the apparent unilateral capacity of the crystal condenser have suggested themselves, but we have decided to make further measurements before entering into an attempt to consider more of the factors of the problem.

Specimen with Soldered Attachment under Test. — We have succeeded in soldering on the electrodes to one specimen now under test, and are able to preserve the condenser for a more extensive study of its characteristics. Up to the present this study has not added anything to the results given above. The new condenser leaks badly in one direction but very little in the opposite direction of charge. We are putting it through an ageing process before submitting it to final measurement.

TABLE VIII.

Equations Used in Calculating Values in Tables VI. and VII.

E.	Point Positive. Equation.	Point Negative. Equation.
.3	....	$I = .0703 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$
.6	$I = .13 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$	$I = .144 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$
.9	$I = .192 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$	$I = .227 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$
1.2	$I = .248 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$	$I = .320 \times 10^{-7} \times n(1 - 2e^{-\frac{165}{n}})$

Microscopic and Electrical Exploration of the Specimens.

Illumination and Magnification. — Plate I. contains some micrographs of fragments of the crystals. These pictures — which are reproduced with a magnification of 20 diameters — were obtained by reflected light, with the aid of an illuminating objective. The light, which entered the side of the objective, was reflected downward by a prism so that it fell nearly perpendicularly upon the face of the crystal. This vertical illumination from above is most favorable for showing the stratifications in the crystals. Viewed by transmitted light the characteristics are hardly discernible.

Micrograph *a*, Plate I, shows two of the crystallographic angles of the carborundum crystal. The distance between these two vertices is 1.6 mm., and will serve as a convenient standard of reference for the dimensions of the other pictures, which were magnified to the same scale.

Conducting and Insulating Strata. — Micrograph *c* shows very clearly the characteristic stratification, which we have found to be the foundation of the electrostatic capacity of the carborundum. The black lines running in a general horizontal direction across the surface of the specimen are outcroppings of conducting dykes of the crystal; while the white spaces separating the black lines are outcroppings of the insulating matrix in which these dykes are imbedded. The lines which are black and white in the pictures are really merely *differently colored* in the crystal. The white regions are generally a transparent blue in the crystals, and the regions reproduced as black are usually seen as brown or red in the specimen.

TABLE IX.

Values of C, RC, and R for Specimen II.

Applied e. m. f. E.	Capacity C, in Micro-farads.	RC in Ohm-farads.	R in Ohms.
For Point Positive			
.6	.0216	.0029	1.34 × 10^5
.9	.0213	.0029	1.36
1.2	.0207	.0029	1.40
For Point Negative			
.3	.0234	.0029	1.24 × 10^5
.6	.0246	.0029	1.18
.9	.0252	.0029	1.14
1.2	.0267	.0029	1.08

The difference in electrical conductivity of the dark and light strata was discovered by mounting the specimen in the field of the microscope, and exploring it with two pin-points serving as electrodes. The pin-point electrodes were connected with a battery and galvanometer, or telephone, and were moved about over the surface of the specimen by means of two independent mechanical microscope stages insulated from each other. By means of the slow motion of the mechanical stages, the two pin-points could be put down upon the same dyke or on two different dykes, or one pin could be placed on a dyke while the other was placed on one of the lighter colored strata separating the dykes.

It was found that the insulation resistance of a very thin layer of the lighter colored material was so great that the current through it under an impressed e. m. f. of 7 volts did not give a perceptible deflection on the galvanometer, that is, the resistance was more than 7000 million ohms, whereas the resistance of the circuit when both pins were upon the same dark-colored dyke was only a few thousand ohms at this voltage.

It was not possible with some of the specimens to get into electrical contact with all of the dark-colored outcroppings, because in some cases it was evident that the outcroppings were in depressions or were coated over so that the electrodes could not be brought against them. With other specimens and with the aid of a telephone receiver in the exploring circuit, we could make attachment of one electrode to a solder-bed in which the crystal was mounted and could draw the other electrode across an exposed face of the crystal in the field of the microscope and hear a click in the telephone as the moving electrode passed over each of the dark-colored outcroppings.

Outcrop of Conducting Points. — In addition to the linear outcroppings of the conducting dykes, there are also with some of the specimens minute points of outcrop of conducting material. Some of these points are visible in Micrograph *d*. They are the globular markings near the left-hand side of the picture. Each globular marking is a minute darker speck surrounded by a whitish circle. In some cases we found an outcrop in the form of a minute speck, which evidently communicated with one or more conducting layers within the crystal, and which showed measurable capacity when one electrode was brought into contact with the speck while the other electrode was in contact with a distant corner of the crystal. In fact, with the specimen of *d* many of the apparently linear outcroppings are made up of discrete points of conducting material.

A Visible Condenser in Micrograph b. — As an illustration of a condenser completely visible, reference is made to Micrograph *b*. The left half of the picture shows two nearly parallel lines running up through the center and down along the left-hand side of the specimen. These lines, which run out of the field at the bottom and top of the picture, were seen, by moving the specimen in the original examination of this specimen, to be really two closed curves, one inside of the other. They are the outcroppings of two practically flat parallel strata nearly perpendicular to the direction of vision. By exploration with the pin-point electrodes these strata were found to be conducting, whereas the whitish band between the dark lines is the outcrop of an insulating layer separating the two conducting strata. Thus we have a visible condenser in the specimen. The capacity of this condenser was too small to be measured by the method we were employing, and this specimen is kept for future investigation.

Micrograph of Specimen I. — The pictures *e* and *f* of Plate I. show micrographs of the two opposite sides, respectively, of Specimen I. The electrical connection of the specimen into the test circuit was by means of screws set up against the two sides of the crystal. The ends of the screws were so large that the exact point of contact of the screws against the crystal could not be accurately determined, but one of the screw contacts was apparently against the ridge near the center of *e*; the other screw contact was near the center of *f*, which is opposite to *e*. Judging from the large value of the capacity obtained, we are of the opinion that more than one conducting dyke was in contact with each electrode, and that we were dealing with a multiple-plate condenser. Of this, however, we cannot at present be certain, as we have not as yet been able to measure the dielectric constant of the insulating strata, and have not yet been able to determine accurately the geometrical dimensions of the crystal condensers.

NOTE ON RELATION OF STRATIFICATION TO ACTION OF CARBORUNDUM CRYSTALS AS DETECTORS FOR ELECTRIC WAVES.

Not all points of a carborundum crystal are equally good detectors for the electric waves of wireless telegraphy. After our discovery of the existence of alternate conducting and insulating strata in the carborundum crystal, we arranged circuits, with the crystal connected to a multiple-pole switch so that it could be thrown into a wireless telegraph circuit and tested for its sensitiveness to electric waves produced by a test buzzer; then into a circuit of the form of Figure 1, and tested for conductivity and capacity.

The crystal was mounted in the field of a microscope and was carried by a mechanical stage with micrometer adjustment so that different parts of the crystal, while under observation with the microscope, could be brought into contact with the pin-point electrode.

It was found that

1. The crystal and its contact (i. e. the detector) did not respond to electric waves, and did not conduct, and did not have capacity when the point electrode was on one of the light-colored strata;

2. The crystal detector did respond whenever the contact was against one of the darker strata. In general, however, no capacity was dis-

cernible with one of these random adjustments sensitive to electric waves;

3. In rare cases, obtainable only after numerous trials, the adjustment of the contact upon the crystal would give a capacity; in these cases the system would also act as a detector for electric waves.

These observations show that the detection of electric waves occurs for practically any conductive high-resistance contact of the electrode with the crystal, whereas only a rarely attainable adjustment of the contact against a conducting stratum that happens to be pretty well insulated from the other electrode gives the capacity effect measurable by the method of charge and discharge. It is however apparent that if the capacity measurements could be made with the high frequency oscillations of wireless telegraphy, the capacity effect would appear much more commonly.

Summary.

1. An electrostatic capacity is found in carborundum.
2. The capacity-measurements with two specimens are given for different voltage and different frequencies of charge and discharge. The capacity of one of the specimens was about .006 microfarads; that of the other about .022 microfarads.
3. With Specimen I. a leak, different in different directions of charge and not obeying Ohm's law, made the measurements uncertain of accurate interpretation.
4. Specimen II. was practically non-leaky but showed incompleteness of charge and discharge such as would be obtained with a high resistance (120,000 ohms) in the circuit. A reduction of the observation on the assumption of incomplete charge and discharge gives a capacity, which for voltages not zero, is different in the two opposite directions of charge. In one direction of charge the capacity increases with increase of applied voltage; while in the opposite direction of charge the capacity decreases with increase of voltage.
5. The existence of capacity in the crystal was found to be due to the existence of numerous alternate conducting and insulating strata within the crystal. These strata are visible with vertical illumination and moderate magnification.
6. Micrographs showing the stratification are given.
7. So far as the present experiments show, the action of the carborundum as a detector for electric waves and as a rectifier for electric currents is independent of its action as a capacity. But it will detect electric waves or rectify only provided contact is made to one or more of

the conducting strata. It may detect electric waves with an adjustment that shows no capacity by the present method of measuring capacity. On the other hand, with every adjustment at which we found capacity, we found also rectification and detection of electric waves.

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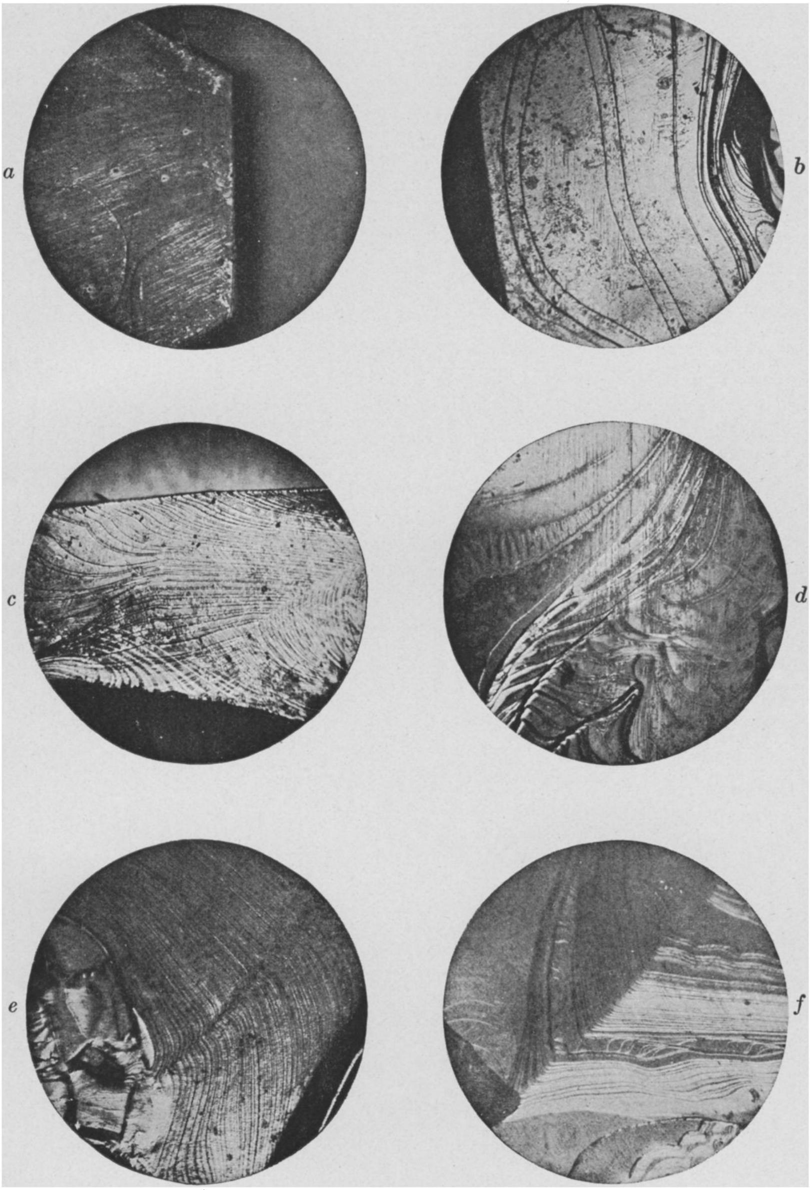
JEFFERSON PHYSICAL LABORATORY,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.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